5.4 BUILDING INNOVATIONS

5.4.1 The Need for Innovations

Had the towers been built according to conventional design, they would have been heavier and would have had less usable space on each floor. Thus, a resourceful approach was taken in translating The Port Authority's needs and Yamasaki's design into practice.

The Investigation Team identified six innovations incorporated in the lateral-load-resisting system and the gravity-load-carrying system of the towers. Their roles were discussed in Chapter 1. In addition, there were two innovations in achieving the required fire resistance ratings. The innovative, tiered elevator system was also discussed in Chapter 1. The following sections describe these new technologies. The use of sprayed fire-resistive material is discussed in more detail in Section 5.6.

5.4.2 Framed Tube System

WTC 1 and WTC 2 were among the first steel-structure, high-rise buildings built using the framed-tube concept to provide resistance to lateral (wind) loads. The framed-tube system had previously been used in the concrete-framed, 43-story DeWitt-Chestnut and the 38-story Brunswick buildings, both in Chicago and both completed in 1965.

In the framed-tube concept, the exterior frame system resists the force of the wind. The exterior columns carry a portion of the building gravity loads, and in the absence of wind, are all in compression, i.e., the loads push down on and shorten the columns. Under the effect of a strong wind alone, columns on the windward side are in tension, i.e., they elongate as the top of the building bends away from the wind. The columns on the leeward side are compressed. The columns on the walls parallel to the wind are half in tension (on the windward side) and half in compression (on the leeward side). The net effect of combined gravity and wind loads is larger compression on the leeward side and reduced compression, or in rare instances even tension, on the windward side.

Prior to final design, tests had been performed at the University of Western Ontario to assess the stiffness of the wall panels, which consisted of three columns, each three stories high, and the associated spandrel plates as shown in Figure 1–4. These tests used quarter-scale thermoplastic models of panels planned for the 20th, 47th, and 74th floors. (Recall that the structural members became lighter at the higher floors.) The tests also examined the effect of the spandrel thickness, the width of the box columns, and the presence and thickness of stiffeners. Forces were applied to the models, and the resulting deflections measured. The results of these tests guided the final design of the wall panels and provided support for The Port Authority's acceptance of the resulting structural design. This included the innovations described in Sections 5.4.3 and 5.4.4.

5.4.3 Deep Spandrel Plates

The standard approach to construction of the framed tube would have used spandrel beams or girders to connect the columns. The towers used a band of deep plates as spandrel members to tie the perimeter columns together.

5.4.4 Uniform External Column Geometry

In a typical high-rise building, the columns would have been larger near the base of the building and would have become smaller toward the top as they bore less wind and gravity loads. However, the Yamasaki design called for the appearance of tall, uniform columns (Figure 1–2). This was achieved by varying both the strength of the steels and the thickness of the plates that made up the perimeter columns.

5.4.5 Wind Tunnel Test Data to Establish Wind Loads

To determine the extreme wind speeds that could be expected at the top of the towers, Worthington, Skilling, Helle & Jackson (WSHJ) collected data on the wind speeds and directions recorded in the New York area over the prior 50 years. From these data, a design wind speed for the buildings was determined for a 50 year wind event, defined as the wind speed, averaged over a 20 min duration at 1,500 ft above the ground. The estimated value was just under 100 mph in all directions.

To estimate how the buildings would perform under wind loads, both during construction and upon completion, WSHJ conducted a then unique wind tunnel testing program at Colorado State University (CSU) and the National Physical Laboratory (NPL) in the United Kingdom. In each wind tunnel, a physical model of Lower Manhattan, including the towers, was subjected to steady and turbulent winds consistent with the estimated design wind speeds. The model scale was 1/500 for the CSU tests and 1/400 for the NPL tests. The tower models were thus about 3 ft tall. Separate tests were conducted for the single tower and for the two towers at various spacings, with various values of the tower stiffness and damping, and for various wind directions. The two laboratories obtained similar results. Tests on the two-tower models showed that the wind response of each tower was significantly affected by the presence of the other tower.

WSHJ also conducted experiments to determine the wind-induced conditions that would be tolerated by the people who would work in and visit the towers. Breaking new ground in human perception testing, the investigators found that surprisingly low building accelerations caused discomfort.

The test results led to changes in the building design, including stiffer perimeter columns, and the addition of viscoelastic dampers described in the next section. The dampers were used to reduce the building vibrations due to winds.

5.4.6 Viscoelastic Dampers

The tower design included the first application of damping units to supplement the framed-tube in limiting wind-induced oscillations in a tall building. Each tower had about 10,000 dampers.

On most truss-framed floors (tenant floors), a damper connected the lower chord of a truss to a perimeter column. A depiction of the units is shown in Figure 5–3. On beam-framed floors (generally the mechanical floors with their heavier loads), a damper connected the lower flange of a wide-flange beam (that spanned between the core and the perimeter wall) to a spandrel.

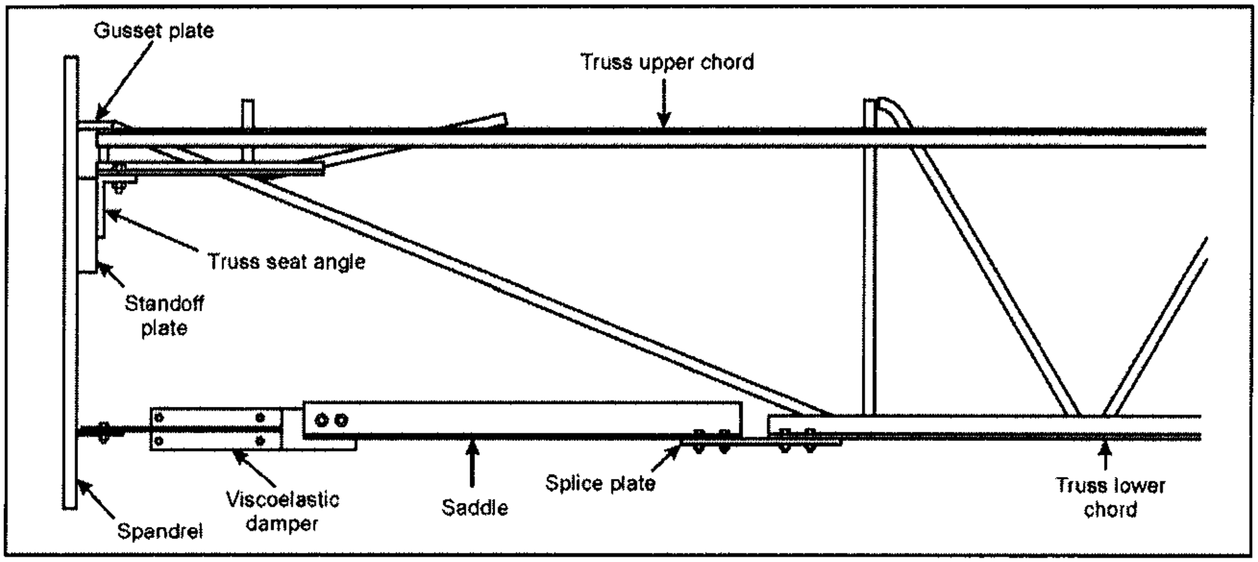


Figure 5–3. Diagram of floor truss showing viscoelastic damper.

Two sets of experiments, conducted by the 3M Company (the manufacturer of the viscoelastic material) and by the Massachusetts Institute of Technology, respectively, examined the damping characteristics of the units. Both studies found that the units provided significant supplemental damping under design conditions.

5.4.7 Long-Span Composite Floor Assemblies

The floor system in the towers (as shown in Figure 1–6) was novel in two respects:

- The use of open-web, lightweight steel trusses topped with a slab of lightweight concrete
- The composite action of the steel and concrete that resulted from the "knuckles" of the truss diagonals extending above the top chord and into the poured concrete

Tests conducted in 1964 by Granco Steel Products and Laclede Steel Company (the manufacturer of the trusses for WTC 1 and WTC 2) determined the effectiveness of the knuckles in providing composite action. Another set of tests, performed by Laclede Steel Company, determined that any failure of the knuckles occurred well beyond the design capacity. A third set of tests, performed at Washington University in 1968, confirmed the prior results and indicated that failure was due to crushing of the concrete near the knuckles.

5.4.8 Vertical Shaft Wall Panels

While similar to other gypsum shaft wall systems and firewalls, the compartmentation system used in the vertical shafts (e.g., for elevators, stairs, utilities and ventilation) was unique in that it eliminated the need for any framing. The walls consisted of gypsum planks placed into metal channels at the floor and ceiling slabs. The planks were 2 in. thick (2½ in. on floors with 16 ft ceiling heights) and 16 in. wide, with metal tongue and groove channels attached to the long sides that served as wall studs. An assembled wall was

then covered with gypsum wallboard. The planks were likely custom fabricated for this job, as the investigators found no mention of similar products in gypsum industry literature of the time or since.

5.5 STRUCTURAL STEELS

5.5.1 Types and Sources

Roughly 200,000 tons of steel were used in the construction of the two WTC towers. The building plans called for an unusually broad array of steel grades and multiple techniques for fabricating the structure from them. The NIST team obtained the information needed to characterize the steels from structural drawings provided by The Port Authority, copies of correspondence during the fabrication stages, steel mill test reports, interviews with fabrication company staff, search of the contemporaneous literature, and measurements of properties at NIST. Sorting through this immense amount of information was made difficult by the large number of fabricators and suppliers, the use of proprietary grades by some of the manufacturers; and the fact that the four fabricators of the impact and fire floor structural elements no longer existed at the time of this Investigation.

Fortunately, the potential for confusion had led the building designers to a tracking system whereby the steel fabricators stamped and/or stenciled each structural element with a unique identifying number. The structural engineering drawings included these identifying numbers as well as the yield strengths of the individual steel components. Thus, when NIST found the identifying number on an element such as a perimeter column panel, the particular steel specified for each component of the element was known, as well as the intended location of the steel in the tower.

In all, 14 grades of steel were specified in the structural engineering plans, having yield strengths from 36 ksi to 100 ksi. Twelve were actually used, as the fabricators were permitted to substitute 100 ksi steel where yield strengths of 85 ksi and 90 ksi were specified. Table 5–1 indicates the elements for which the various grades were used. The higher yield strength steels were used to limit building weight while providing adequate load-carrying capacity.

Table 5–1. Specified steel grades for various applications.

Application	Yield Strength (ksi)											
	36	42	45	46	50	55	60	65	70	75	80	100
Perimeter columns	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Spandrel plates	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Core columns	✓	✓	(a)		(a)							
Floor trusses	✓				✓							

a. About 1 percent of the wide flange core columns were specified to be of these higher grades.

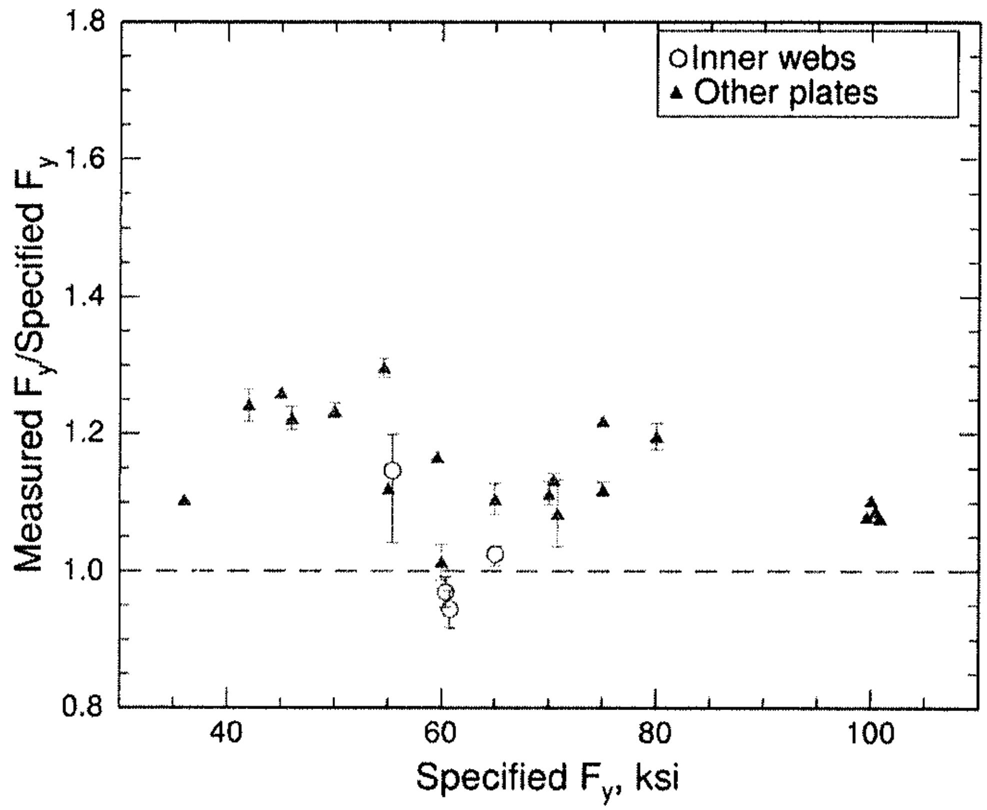
5.5.2 Properties

The Port Authority required a thorough and detailed quality assurance programs to ensure compliance with the specifications for the steel, welds, and bolts. The steel data went beyond the minimum yield strength (the property of greatest importance) to include tensile strength and ductility. The quality assurance program included unannounced inspections and confirming tests.

NIST performed confirmatory tests on samples of the 236 pieces of recovered steel to determine if the steel met the structural specifications. Making a definitive assessment was complicated by overlapping specifications from multiple suppliers, differences between the NIST test procedures and the test procedures that originally qualified the steel, the natural variability of steel properties, and damage to the steel from the collapse of the WTC towers. Nonetheless, the NIST investigators were able to determine the following:

- There were 14 grades (strengths) of steel that were specified. However, a total of 32 steels in the impact and fire floors were sufficiently different (grade, supplier, and gage) to require distinct models of mechanical properties.
- The steels in the perimeter columns met their intended specifications for chemistry, mechanical properties, yield strengths, and tensile properties. The steels in the core columns generally met their intended specifications for both chemical and mechanical properties.
- Roughly 13 percent of the measured strength values for the perimeter and core columns were at or below the specified minimums (Figure 5–4). The strength variation was consistent with the historical variability of steel strength and with the effects from damage during the collapse of the towers. The measured values were within the typical design factor of safety.
- The yield strengths of many of the steels in the floor trusses were above 50 ksi, even when they were specified to be 36 ksi.
- Tests on a limited number of recovered bolts showed they were much stronger than expected based on reports from the contemporaneous literature.

The mechanical properties of steel are reduced at elevated temperatures. Based on measurements and examination of published data, NIST determined that a single representation of the elevated temperature effects on steel mechanical properties could be used for all WTC steels. Separate values were used for the yield and tensile strength reduction factors for bolt steels.



Note: The ratio values less than 1 arose from natural variation in the steel and did not affect the safety of the towers on September 11, 2001. The bars represent maximum and minimum values from multiple measurements.

Figure 5–4. Ratio of measured yield strength (F_y) to specified minimum yield strength for steels used in WTC perimeter columns.

5.6 FIRE PROTECTION OF STRUCTURAL STEEL

5.6.1 Thermal Insulation

When steel is heated it loses both strength and stiffness. Thus, measures must be taken to protect the steel in a structure from temperature rise (and consequent loss of strength) in case of fire.

Bare structural steel components can heat quickly when exposed to a fire of even moderate intensity. Therefore, some sort of thermal protection, or insulation, is necessary. This insulation can be in direct contact with the steel, such as a sprayed fire-resistive material (SFRM), or can be a fire resistant enclosure surrounding a structural element.

5.6.2 Use of Insulation in the WTC Towers

The thermal protection of the steel structures in the WTC towers included a combination of SFRM and enclosures of gypsum wallboard. The use of SFRM for floor truss protection was new in high-rise buildings, and the requirements evolved during the construction and life of the towers. By examining documents supplied by The Port Authority, LERA, and the SFRM manufacturers, NIST was able to

document much of the sequence of these changing requirements and arrive at an estimation of the passive protection in place on September 11, 2001.

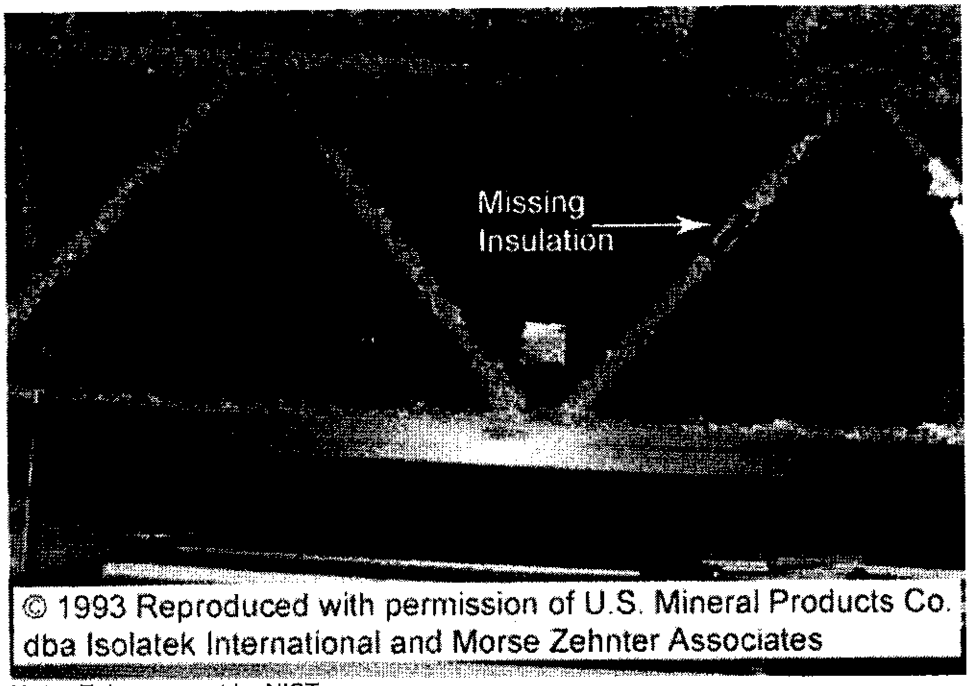
Floor Systems

At the time the WTC was designed, the ASTM E 119 test method had been used for nearly 50 years to determine the fire resistance of structural members and assemblies. However, The Port Authority confirmed to the Investigation Team that there was no record of fire endurance testing of the innovative assemblies representing the thermally protected floor system used in the towers. The floor assembly was not tested despite the fact that the Architect of Record and the Structural Engineer of Record stated that the fire rating of this novel floor system could not be determined without testing.

Prior to construction, the Architect of Record had used information from (unidentified) manufacturers to recommend a 1 in. thickness of SFRM around the top and bottom chords of the trusses and a 2 in. thickness for the web members of the trusses. This was to achieve the fire endurance requirements for Class 1A construction (Section 5.3.3).

In 1969, The Port Authority directed that a ½ in. thick coating of BLAZE-SHIELD Type D (BLAZE-SHIELD D), a mixture of cement and asbestos fibers, be used to insulate the floor trusses. This was to achieve a Class 1A rating, even though the preponderance of evidence suggests that the towers were chosen to be Class 1B, the minimum required by the NYC Building Code. NIST found no evidence of a technical basis for selection of the ½ in. thickness. This coating had been installed as high as the 38th floor of WTC 1 when its use was discontinued due to recognition of adverse health effects from inhalation of asbestos fibers. The spraying then proceeded with BLAZE-SHIELD DC/F, a similar product in which the asbestos was replaced by a glassy mineral fiber and whose insulating value was reported by Underwriters Laboratories, Inc., to be slightly better than that of BLAZE-SHIELD D. On the lower floors, the BLAZE-SHIELD D was encapsulated with a sprayed material that provided a hard coat to mitigate the dispersion of asbestos fibers into the air.

In 1994, The Port Authority measured the SFRM thickness on trusses on floors 23 and 24 of WTC 1. In all, average thicknesses were reported for 32 locations, and the overall average thickness was found to be 0.74 in. NIST performed a further evaluation of the SFRM thickness using photographs taken in the 1990s of floor trusses on (non-upgraded) floors 22, 23, and 27 of WTC 1 (Figure 5–5). By measuring dimensions on the photographs, NIST estimated the insulation thicknesses on the diagonal web members of trusses. (The thickness of chord member insulation could not be measured.) The average thickness and standard deviation of web members was 0.6 in. ± 0.3 in. on the main trusses, 0.4 in. ± 0.25 in. on the bridging trusses, and 0.4 in. ± 0.2 in. on the diagonal struts. These numbers indicated that there were areas where the coating thickness was less than the specified 0.5 in.



Note: Enhancement by NIST.

Figure 5–5. Irregularity of coating thickness and gaps in coverage on SFRM–coated bridging trusses.

In 1995, The Port Authority performed a study to establish requirements for retrofit of sprayed insulation to the floor trusses during major alterations when tenants vacated spaces in the towers. Based on design information for fire ratings of a similar, but not identical, composite floor truss system contained in the Fire Resistance Directory published by Underwriters Laboratories, Inc., the study concluded that a 1½ in. thickness of sprayed mineral fiber material would provide a 2 hour fire rating, consistent with the Class 1B requirements. In 1999, the removal of existing SFRM and the application of new material to this thickness became Port Authority policy for full floors undergoing new construction and renovation. For tenant spaces in which only part of a floor was being modified, the SFRM needed only to be patched to ¾ in. thickness or to match the 1½ in. thickness, if it had previously been upgraded. In the years between 1995 and 2001, thermal protection was upgraded on 18 floors of WTC 1, including those on which the major fires occurred on September 11, 2001, and 13 floors of WTC 2 that did not include the fire floors. The Port Authority reported that the insulation used in the renovations was BLAZE-SHIELD II.

In July 2000, an engineering consultant to The Port Authority issued a report on the requirements of the fire resistance of the floor system of the towers. Based on calculations and risk assessment, the consultant concluded that the structural design had sufficient inherent fire performance to ensure that the fire condition was never the critical condition with respect to loading allowances. The report recommended that a 1.3 in. thickness be used for the floor trusses.

In December 2000, another condition assessment concluded that the structural insulation in the towers had an adequate 1 hour rating, considering that all floors were now fitted with sprinklers. The report also noted the ongoing Port Authority program to upgrade the fire-resistive material thickness to 1½ in. in order to achieve a 2 hour fire rating.

The Port Authority provided NIST with the records of measurements of SFRM thickness on upgraded floors in both towers. The average thickness and standard deviation on the main trusses was 2.5 in. ± 0.6 in., based on 18 data sets with a total of 256 measurements. NIST analysis of several Port Authority photographs from the 1990s of the upgraded 31st floor of WTC 1 indicated an average thickness and standard deviation on the main trusses of 1.7 in. ± 0.4 in., based on 52 measurements from five web members in two photographs. NIST gave more weight to the measured data, which were taken according to a standard procedure in ASTM E 605, than to the data scaled from photographs, for which there was neither standard procedure nor calibration of the method.

Perimeter Columns

In 1966, the contractor responsible for insulating the perimeter columns proposed applying a 1 3/16 in. thick coating of BLAZE-SHIELD D to the three external faces (Figure 5–6) to achieve a 4 hour rating, which is a Class 1A rating requirement (1 hour more than Class 1B). NIST found evidence of a technical basis for this decision. In the construction drawings prepared by the exterior cladding contractor, the following SFRM thicknesses were specified:

- 7/8 in. of vermiculite plaster on the interior face and 1 3/16 in. of BLAZE-SHIELD D on the other three faces.
- ½ in. of vermiculite plaster on the interior surfaces of the spandrels and ½ in. of BLAZE-SHIELD D on the exterior surfaces.

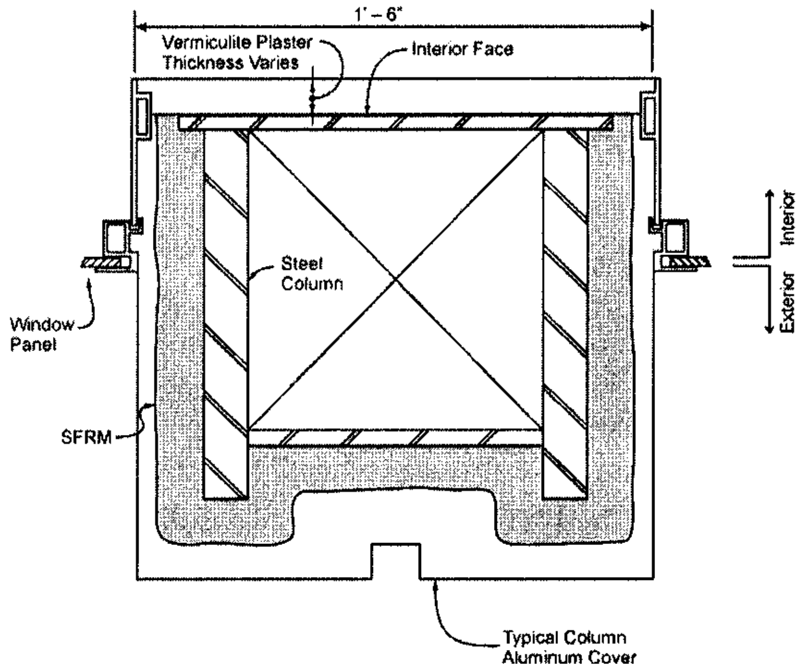


Figure 5–6. Thermal insulation for perimeter columns.

Vermiculite plaster had a higher thermal conductivity and thereby increased heat migration from the room air to the column steel and, thus, could keep the steel temperature at 70 °F when the temperature was 0 °F outside.

In October 1969, The Port Authority provided the following instructions to the contractor applying the sprayed fire protection, in order to maintain the Class 1-A Fire Rating of the NYC Building Code:

- 2 3/16 in. of BLAZE-SHIELD D for columns smaller than 14WF228[12] and 1 3/16 in. for columns equal to or greater than 14WF228.
- ½ in. covering of BLAZE-SHIELD D for beams, spandrels and bar joists.

NIST's review of available documents has not uncovered the reasons for selecting BLAZE-SHIELD fire-resistive material or the technical basis for specifying ½ in. thickness of SFRM for the floor trusses. As with the trusses, BLAZE-SHIELD DC/F was applied to the perimeter columns above the 38th floor of WTC 1 and all the perimeter columns in WTC 2.

Core Columns and Beams

Multiple approaches were used to insulate structural elements in the core:

- Those core columns located in rentable and public spaces, closets, and mechanical shafts were enclosed in boxes of gypsum wallboard (and thus were inaccessible for inspection). The amount of the gypsum enclosure in contact with the column varied depending on the location of the column within the core. SFRM (BLAZE-SHIELD D and DC/F) was applied on those faces that were not protected by the gypsum enclosure. The thicknesses specified in the construction documents were 1 3/16 in. for the heavier columns and 2 3/16 in. for the lighter columns.
- Columns located at the elevator shafts were protected using the same SFRM thicknesses. They were not enclosed and thus were accessible for routine inspections.

Inspection of the columns within the elevator shaft spaces in 1993 indicated some loss of SFRM coverage. As a result, new insulation was applied to selected columns within the elevator shaft space. Information provided to NIST indicated that a different SFRM, Monokote Type 2-106, was used. Thickness measurements for columns and beams below the 45th floor indicated average thicknesses of 0.82 in. and 0.97 in., respectively. Information from The Port Authority indicated that the minimum required thickness of the re-applied SFRM was ½ in. for the columns and ¾ in. for the beams.

NIST was unable to locate information from which to characterize the insulation of the core columns and beams that were not accessible. Except as noted above, once completed, the core was generally not inspected. NIST was not able to locate any post-collapse core beams or columns with sufficient insulation still attached to make pre-collapse thickness measurements.

Summary of SFRM on September 11, 2001

Table 5–2 summarizes the types and thicknesses of the SFRMs used in the towers. According to Port Authority documents, in the upper part of the towers, trusses on floors 92 through 100 and 102 in WTC 1

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[12] This designation indicates that the column is a 14 in. deep wide flange section and weighs 228 pounds per foot.

had upgraded insulation by September 11, 2001. In WTC 2, truss insulation had been upgraded on floors 77, 78, 85, 88, 89, 92, 96, 97, and 99.

Table 5–2. Types and locations of SFRM on fire floors.

Building Component	Material	Thickness (in.)		
		Specified[a]	Installed	Used in Analysis[b]
FLOOR SYSTEM				
Original				
Main trusses and diagonal struts	BLAZE-SHIELD DC/F	0.5	0.75	0.6
Bridging trusses (one-way zone)[c]	BLAZE-SHIELD DC/F	0.5	0.38[d]	0.3
Bridging trusses (two-way zone)[c]	BLAZE-SHIELD DC/F	0.5	0.38[d]	0.6
Upgraded				
Main trusses	BLAZE-SHIELD II	1.5	2.5	2.2
Main truss diagonal struts	BLAZE-SHIELD II	1.5	2.5	2.2
Bridging trusses	BLAZE-SHIELD II	1.5	2.5	2.2
EXTERIOR WALL PANEL				
Box columns				
Exterior face	BLAZE-SHIELD DC/F	1 3/16	(e)	1.2
Interior face	Vermiculite plaster	7/8	(e)	0.8
Spandrels				
Exterior face	BLAZE-SHIELD DC/F	0.5	(e)	0.5
Interior face	Vermiculite plaster	0.5	(e)	0.5
CORE COLUMNS				
Wide flange columns				
Light	BLAZE-SHIELD DC/F	2 3/16	(e)	2.2
Heavy	BLAZE-SHIELD DC/F	1 3/16	(e)	1.2
Box columns				
Light	BLAZE-SHIELD DC/F	(f)	(e)	2.2[(g)]
Heavy	BLAZE-SHIELD DC/F	(f)	(e)	1.2[(g)]
CORE BEAMS	BLAZE-SHIELD DC/F	0.5	(e)	0.5

a. "Specified" means material and thicknesses determined from correspondence among various parties.
b. The analysis is described in Chapter 6.
c. Not expressly specified. SFRM was required for the areas where the main trusses ran in both directions and, while not required, was also applied in the areas where they ran in one direction only.
d. Analysis of photographs indicated that the thickness was approximately one half that on the main trusses.
e. Not able to determine.
f. Not specified.
g. Thickness assumed equal to wide flange columns of comparable weight per foot.

5.7 CONCRETE

Two types of concrete were used for the floors of the WTC towers: lightweight concrete in the tenant office areas and normal weight concrete in the core area. Because of differences in composition and weight, the two types of concrete respond differently to elevated temperatures, as shown in Figure 5–7. While their tensile strengths degrade identically, lightweight concrete retains more of its compressive strength at higher temperatures. The degradation of concrete mechanical properties with temperature was included in the structural response analysis of the floor systems.

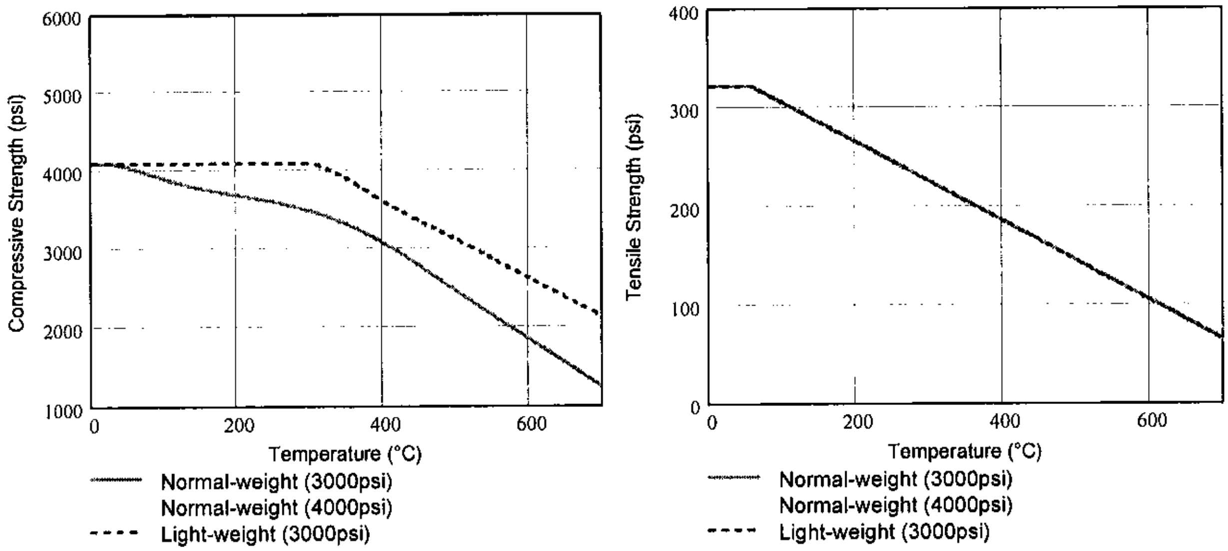

Figure 5–7. Temperature–dependent concrete properties.

5.8 THE TENANT SPACES

5.8.1 General

About 80 percent of the floors had a single tenant. Many of these floors were filled with arrays of modular office cubicles, their low partitions affording sightlines to the windows, with perhaps an occasional perimeter conference room or executive office in the way (Figure 1–11). Trading floors (Figure 1–12) had tables and computers throughout and food service areas to minimize time away from the non-stop transactions. The remaining 20 percent of the floors were each subdivided among as many as 25 tenants. Some of the approximately 25 tenants that occupied two or more contiguous floors installed convenience stairways within their own space.

Certain floors were of special interest to the Investigation. These were the floors on which there was structural damage from the aircraft and/or on which extensive fires were observed. These floors, designated as focus floors, and the information NIST obtained regarding them are characterized in Table 5–3. Additional information, obtained from the tenant firms and The Port Authority, is summarized in the remainder of this chapter.

5.8.2 Walls

The plans for the tenant spaces in WTC 1 showed no interior walls whose sole function was to subdivide the floors. There were a number of partitioned offices and conference areas. Although NIST was not able to obtain layout drawings for the fire floors in WTC 2, the verbal descriptions of those floors indicated similarly open space. The types of interior walls were described in Section 5.3.4.

5.8.3 Flooring

Truss-supported concrete slabs formed the floors in the office areas of the towers. Some tenants had installed slightly raised (6 in.) floors on top of the slab under which communication cables were run. This was especially true on trading floors. There was a wide range of floor coverings in use. Inlaid wood and marble were used in some reception areas. Most commonly, the expanse of the floor was covered with nylon carpet.

5.8.4 Ceilings

There were two different ceiling tile systems originally installed in the towers under Port Authority specification. The framing for each was hung from the bottom of the floor trusses, resulting in an apparent room height of 8.6 ft and an above-ceiling height of about 3.4 ft. The tiles in the tenant spaces were 20 in. square, ¾ in. thick, lay-in pieces on an exposed tee bar grid system. The tiles in the core area were 12 in. square, ¾ in. thick, mounted in a concealed suspension system. Neither system was specified to be fire-rated, and it was estimated that in a fire they might provide only 10 min to 15 min of thermal protection to the trusses before the ceiling frame distorted and the tiles fell. Chemically, the tiles were similar, and their combustible content, flame spread, and smoke production were all quite low.

5.8.5 Furnishings

The decorating styles of the tower tenants ranged from simple, modular trading floors to customized office spaces. The most common layout of the focus floors was a continuous open space populated by a large array of workstations or cubicles (Figure 1–11). The number of different types of workstations in the two towers was probably large. However, discussions with office furniture distributors and visits to showrooms indicated that, while there was a broad range of prices and appearances, the cubicles were fundamentally similar to that shown in Figure 5–8.

Source: Reproduced with permission of The Port Authority of New York and New Jersey.

Figure 5–8. A WTC workstation.

The workstations were typically 8 ft square, bounded on all four sides by privacy panels, with an entrance opening in one side only. Within the area defined by the panels was a

self-contained workspace: desktop (almost always a wood product, generally with a laminated finish), file storage, bookshelves, carpeting, chair, etc. Presumably there were a variety of amounts and locations of paper, both exposed on the work surfaces and contained within the file cabinets and bookshelves. The cubicles were grouped in clusters or rows, with up to 215 units on a given floor.

NIST estimated the combustible fuel loading on these floors to have been about 4 lb/ft^2 (20 kg/m^2), or about 60 tons per floor. This was somewhat lower than found in prior surveys of office spaces. The small number of interior walls, and thus the minimal amount of combustible interior finish, and the limited bookshelf space account for much of the differences. While paper in the filing cabinets might have been significant in mass, it did not burn readily due to the limited oxygen available within the drawers.

Table 5–3. Floors of focus.

Building	Floor	Tenant	Damage[a]	Fires[b]	Material Obtained[c]	General Description of Tenant Layout
WTC 1	92	Carr Futures, empty		Y	FP (Carr), V	
	93	Marsh & McLennan (M&M), Fred Alger Mgmt.	Y	Y	FP, F, V	M&M occupied the south side. Filled with workstations. Demising walls for the south façade to the edges of the core. Offices along the east side of the south core wall. Stairwell to the 94th floor.
	94	Marsh & McLennan	Y	Y	FP, F, V	Generally open space filled with workstations. Offices and conference rooms around most of the perimeter. Stairwell to the 93rd floor.
	95	Marsh & McLennan	Y	Y	FP, F, V	Generally open space filed with workstations. Offices, conferences and work areas in exterior corners. Large walled data center along north and east sides. Two separate stairwells, one to 94th floor, the other to the 96th and 97th floors.
	96	Marsh & McLennan	Y	Y	FP, F, V	Generally open space filled with workstations. Offices at exterior corners and middle of north and south facades. Some conference rooms on north and south sides of core. Stairwell connection to 95th and 97th floors.
	97	Marsh & McLennan	Y	Y	FP, F, V	Generally open space filled with workstations. Offices at exterior corners and in the middle of the north façade. Two separate stairwells: one connected to the 95th and 96th floors, the other connected to the 98th, 99th, and 100th floors.
	98	Marsh & McLennan	Y	Y	FP, F, V	Generally open space filled with workstations. Offices at exterior corners and middle of north and south facades. Some conference rooms on north and south sides of core. Stairwell connected to the 97th, 99th, and 100th floors.
	99	Marsh & McLennan	Y	Y	FP, F, V	Open space filled with workstations on the east side and east half of the north side. Offices at exterior corners and along south and west sides. Large walled area on west side of north façade. Stairwell connected to the 97th, 98th, and 100th floors.
	100	Marsh & McLennan		Y	FP, F, V	Considerable number of workstations, but more individual offices than the other floors. Partitioned offices extended the full length of the west wall and also at other locations along walls and at exterior corners. Stairway connected to the 97th, 98th, and 99th floors.
	104	Cantor Fitzgerald		Y	V	Trading floor. Tables with many monitors.

Building	Floor	Tenant	Damage[a]	Fires[b]	Material Obtained[c]	General Description of Tenant Layout
WTC 2	77	Baseline	Y	Y	FP, V	Generally open space. Offices along east and west core walls. A few offices in each exterior corner of the floor.
	78	Baseline, 1st Commercial Bank	Y	Y	FP,V	West side open. Northeast quadrant walled. Offices along south side of east core wall. Offices along east side of south façade.
	79	Fuji Bank	Y	Y	V	
	80	Fuji Bank	Y	Y	FP, V	Generally open space filled with workstations. Offices or conference rooms at exterior corners and along south half of west façade. Large vault at southeast corner of core.
	81	Fuji Bank	Y	Y	V	
	82	Fuji Bank	Y	Y	V	
	83	Chuo Mitsui, IQ Financial	Y		V	Chuo Mitsui had half the area. Wide open space. No information regarding IQ Financial.
	84	Eurobrokers	Y		V	Open floor for trading. Tables rather than workstations. Perimeter offices.
	85	Harris Beach	Y		FP. V	Offices around full perimeter. Offices along east, west and south walls of core.

a. Floors on which the exterior photographs indicated direct damage from the aircraft.
b. Floors on which the exterior photographs indicated extensive or sustained fires.
c. Types of descriptive material obtained: FP, floor plan; F, documentation of furnishings; V, verbal description of interior.

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Chapter 6
RECONSTRUCTION OF THE COLLAPSES

6.1 APPROACH

The following presents an overview of the methods used to reach the accounts in Part I. The details may be found in the companion reports to this document, which are indexed in Appendix C.

A substantial effort was directed at establishing the baseline performance of the WTC towers, i.e., estimating the expected performance of the towers under normal design loads and conditions. This enabled meeting the third objective of the Investigation, as listed in the Preface to this report. The baseline performance analysis also helped to estimate the ability of the towers to withstand the unexpected events of September 11, 2001. Establishing the baseline performance of the towers began with the compilation and analysis of the procedures and practices used in the design, construction, operation, and maintenance of the structural, fire protection, and egress systems of the WTC towers. The additional components of the performance analysis were:

- The standard fire resistance of the WTC truss-framed floor system,
- The quality and properties of the structural steels used in the towers, and
- The response of the WTC towers to design gravity and wind loads.

The second substantial effort was the simulation of the behavior of each tower on September 11, 2001, providing the basis for meeting the first and second objectives of the Investigation. This entailed four modeling steps:

1. The aircraft impact into the tower, the resulting distribution of jet fuel, and the damage to the structure, partitions, insulation materials, and building contents.
2. The spread of the multi-floor fires.
3. The heating of the structural elements by the fires.
4. The response of the damaged and heated building structure, and the progression of structural component failures leading to the initiation of the collapse of the towers.

For such complex structures and complex thermal and structural processes, each of these steps stretched the state of the technology and tested the limits of software tools and computer hardware. For example, the investigators advanced the state-of-the-art in the measurement of construction material properties and in structural finite element modeling. New modeling capability was developed for the mapping of fire-generated environmental temperatures onto the building structural components.

For the final analyses, four cases were used, each involving all four of the modeling steps. Case A and Case B were for WTC 1, with Case B generally involving more severe impact and fire conditions than

Case A. For WTC 2, Case D involved more severe impact and fire conditions than Case C. The results of the two cases for each tower provided some understanding of the uncertainties in the predictions.

There were substantial uncertainties in the as-built condition of the towers, the interior layout and furnishings, the aircraft impact, the internal damage to the towers (especially the insulation), the redistribution of the combustibles, and the response of the building structural components to the heat from the fires. To increase confidence in the simulation results, NIST used information from an extensive collection of photographs and videos of the disaster, eyewitness accounts from inside and outside the buildings, and laboratory tests involving large fires and the heating of structural components. Further, NIST applied formal statistical methods to identify those parameters that had the greatest effect on the model output. These key inputs were then varied to determine whether the results were reasonably robust.

The combined knowledge from all the gathered data and analyses led to the development of a probable collapse sequence for each tower,[13] the identification of factors that contributed to the collapses, and a list of factors that could have improved building performance or otherwise mitigated the loss of life.

6.2 DEVELOPMENT OF THE DISASTER TIMELINE

Time was the unifying factor in combining photographic and video information, survivor accounts, emergency calls from within the towers, and communications among emergency responders. The visual evidence was the most abundant and the most detailed.

The destruction of the WTC towers was the most heavily photographed disaster in history. The terrorist attacks occurred in an area that is the national home base of several news organizations and has several major newspapers. New York City is also a major tourist destination, and visitors often carry cameras to record their visits. Further, the very height that made the towers accessible to the approaching aircraft also made them visible to photographers. As a result there were hundreds of both professional and amateur photographers and videographers present, many equipped with excellent equipment and the knowledge to use it. These people were in the immediate area, as well as at other locations in New York and New Jersey.

There was a surprisingly large amount of photographic material shot early, when only WTC 1 was damaged. By the time WTC 2 was struck, the number of cameras and the diversity of locations had increased. Following the collapse of WTC 2, the amount of visual material decreased markedly as people rushed to escape the area and the huge dust clouds generated by the collapse obscured the site. There is a substantial, but less complete, amount of material covering the period from the tower collapses to the collapse of WTC 7 late the same afternoon.

[13] The focus of the Investigation was on the sequence of events from the instant of aircraft impact to the initiation of collapse for each tower. For brevity in this report, this sequence is referred to as the "probable collapse sequence," although it does not actually include the structural behavior of the tower after the conditions for collapse initiation were reached and collapse became inevitable.

There were multiple sources of visual material:

- Recordings of newscasts from September 11 and afterward, documentaries, and other coverage provided information and also pointed toward other potential sources of material.
- Web sites of the major photographic clearinghouses.
- Local print media.
- NYPD and FDNY.
- Collections of visual material assembled for charitable or historical purposes.
- Individuals' photographs and videos that began appearing on the World Wide Web as early as September 11, 2001.
- Responses to public appeals for visual material by the Investigation Team.

Investigation staff contacted each of the sources, requested the material, made arrangements for its transfer, and addressed copyright and privacy issues. Emphasis was placed on obtaining material in a form as close as possible to the original in order to maintain as much spatial and timing information as possible: direct digital copies of digital photographs and videos, high resolution digitized copies of film or slide photographs, and direct copies from the original source of analog video.

The assembled collection included:

- 6,977 segments of video footage, totaling in excess of 300 hours. The media videos included both broadcast material and outtakes. Additionally, NIST received videotapes recorded by more than 20 individuals.
- 6,899 photographs from at least 200 photographers. As with the videos, many of the photographs were unpublished.

This vast amount of visual material was organized into a searchable database in which each frame was characterized by a set of attributes: photographer (name and location), time of shot/video, copyright status, content (including building, face(s), key events (plane strike, fireballs, collapse), the presence of FDNY or NYPD people or apparatus, and other details, such as falling debris, people, and building damage).

The development of a timeline for fire growth and structural changes in the WTC buildings required the assignment of times of known accuracy to each video frame and photograph. Images were timed to a single well-defined event. Due to the large number of different views available, the chosen event was the moment the second plane struck WTC 2, established from the time stamps in the September 11 telecasts. Based on four such video recordings, the time of the second plane impact was established as 9:02:59 a.m.

> The TV network clocks were quite close to the actual time since they were regularly updated from highly accurate geopositioning satellites or the precise atomic-clock-based timing signals provided by NIST as a public service.

Absolute times were then assigned to all frames of all videos that showed the second plane strike. By matching photographs and other videos to specific events in these initially assigned videos, the time assignments were extended to visual materials that did not include the primary event. Times were also cross-matched using additional characteristics, such as the appearance and locations of smoke and fire plumes, distinct shadows cast on the buildings by these plumes, the occurrence of well-defined events such as a falling object, and even a clock being recorded in an image. By such a process, it was possible to place photographs and videos extending over the entire day on a single timeline. As the time was assigned to a particular photograph or video, the uncertainty in the assignment was also logged into the database. In all, 3,032 of the catalogued photographs and 2,673 of the video clips in the databases were timed with accuracies of ± 3 s or better.

This process enabled establishing the times of four major events of September 11, listed in Table 6–1. The building collapse times were defined to be the point in time when the entire building was first observed to start to collapse.

Table 6–1. Times for major events on September 11, 2001.

Event	Time
First Aircraft Strike	8:46:30 a.m.
Second Aircraft Strike	9:02:59 a.m.
Collapse of WTC 2	9:58:59 a.m.
Collapse of WTC 1	10:28:22 a.m.

There were additional sources of timed information. Phone calls from people within the building to relatives, friends, and 9-1-1 operators conveyed observations of the structural damage and developing hazards. Communications among the emergency responders and from the building fire command centers contributed further information about the areas where the external photographers had no access.

6.3 LEARNING FROM THE VISUAL IMAGES

The photographic and video images were rich sources of information on the condition of the buildings following the aircraft impact, the evolution of the fires, and the deterioration of the structure. To enable analysis of this information, a shorthand notation (based on the building design drawings) was used to label the exterior columns and windows of the buildings:

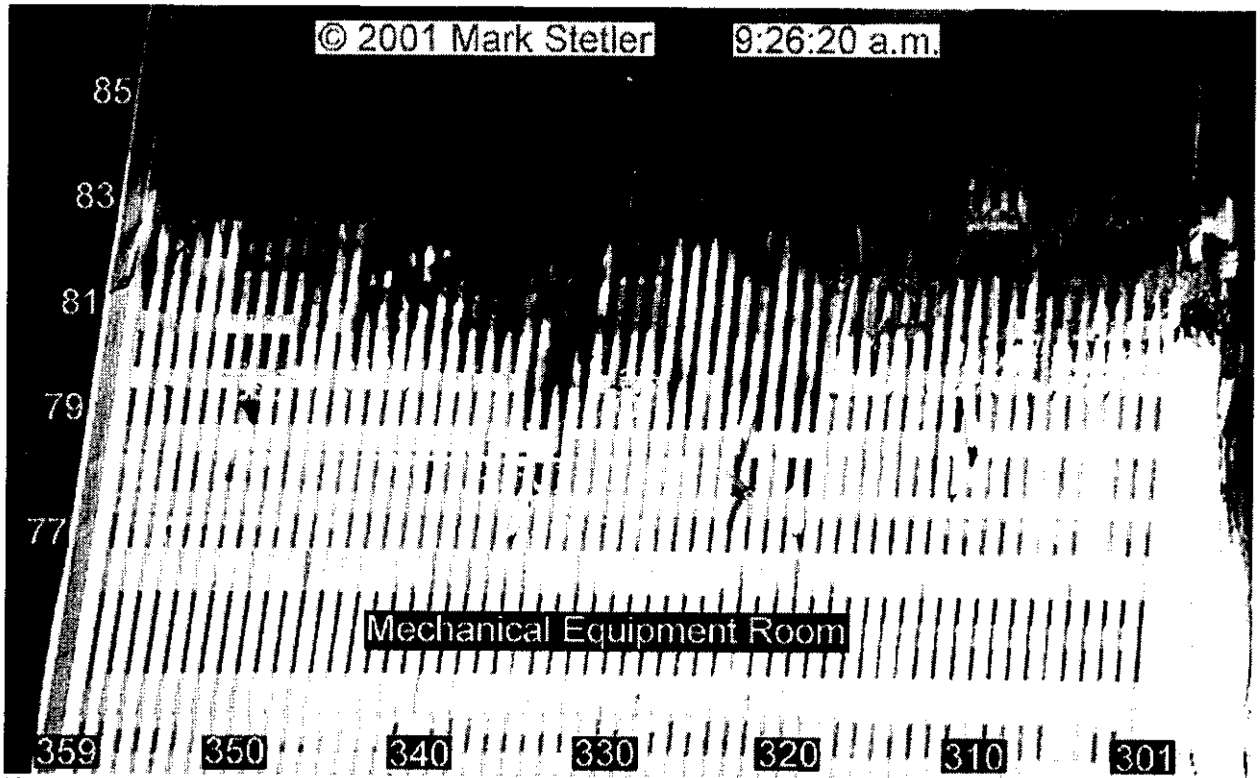
- First, the faces of the towers were numbered in a manner identical to those used in the original plans:

WTC 1:	north: 1	east: 2	south: 3	west: 4
WTC 2:	west: 1	north: 2	east: 3	south: 4

- The 59 columns across each tower face were assigned three-digit numbers. Following the floor number, the first digit was that of the face, and the remaining two digits were assigned consecutively from right to left as viewed from outside the building. Thus, the fourth column from the right on the east face of the 81st floor of WTC 1 was labeled 81-204.

- Each of the 58 windows on each floor and tower face was assigned the number of the column to its right as viewed from the outside of the building and was also identified by its floor. Thus the rightmost window on the east face of the 94th floor of WTC 1 was labeled 94-201.

As an example of information that was extracted, Figure 6–1 shows an enhanced image of the east face of WTC 2. Figure 6–2 expands a section of interest. The amount of detail available is evident. For instance, large piles of debris are present on the north side of the tower on the 80th and 81st floors, and locations where fires are visible or where missing windows are easily identified. Many details of each frame were important in tracking the evolution of the fires and the damage to the buildings.



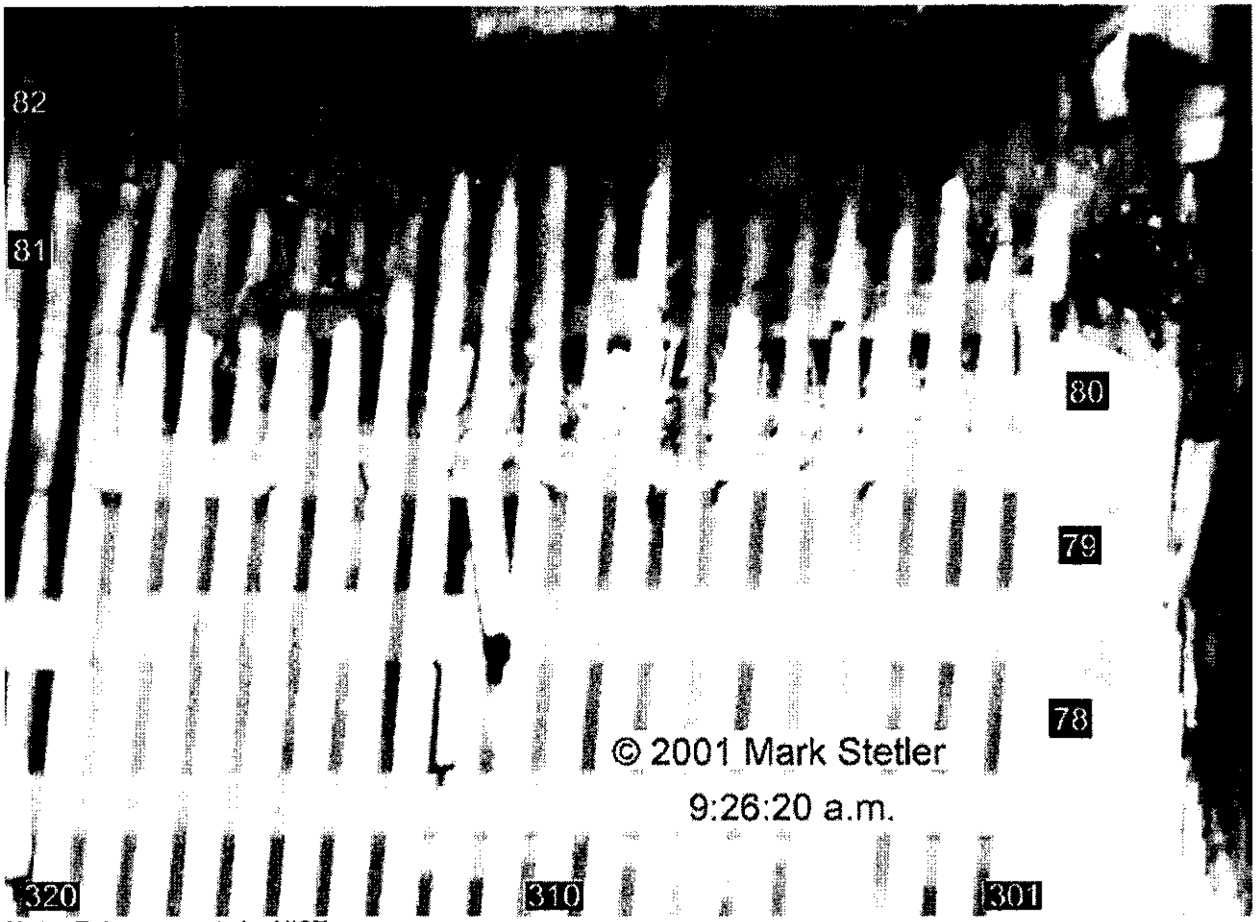
Note: Enhancements by NIST.

Figure 6–1. 9:26:20 a.m. showing the east face of WTC 2.

In each photograph and each video frame, each window was also coded to indicate whether the window was still in place or not and the extent to which flames and smoke were visible. Color-coded graphics of the four façades of the two towers were then constructed. Examples of these graphics were shown in Chapters 2 and 3.

The results of the visual analysis included:

- The locations of the broken windows, providing information on the source of air to feed the fires within.
- Observations of the spread of fires.
- Documentation of the location of exterior damage from the aircraft impact and subsequent structural changes in the buildings.



Note: Enhancements by NIST.

Figure 6–2. Close-up of section of Figure 6–1.

- Identification of the presence or absence of significant floor deterioration at the building perimeter.
- Observations of certain actions by building occupants, such as breaking windows.

The near-continuous observations of the externally visible fires provided input to the computer simulations of fire growth and spread. The discrete observations of changes in the displacement of columns and, to a far lesser degree, floors became validation data for the modeling of the approach to structural collapse of the towers. Table 6–2 lists the most important observations.

6.4 LEARNING FROM THE RECOVERED STEEL

6.4.1 Collection of Recovered Steel

NIST had two reasons for obtaining specimens of structural steel from the collapsed towers. The primary objective was characterizing the quality of the steel and determining its properties for use in the structural modeling and analysis of the collapse sequences. The second reason was obtaining information regarding the behavior of the steel in the aircraft impact zone and in areas which had major fires.

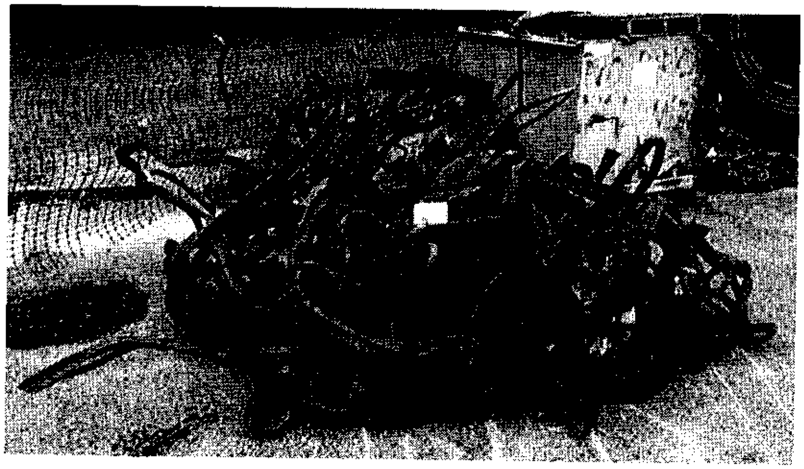
Table 6–2. Indications of major structural changes up to collapse initiation.

Tower	Time (a.m.)	Observation
WTC 1	10:18	Smoke suddenly expelled on the north face (floors 92, 94, 95 to 98) and west face (92, 94 to 98).
	10:23	Inward bowing of perimeter columns on the east side of the south face from floors 94 to 100; maximum extent: 55 in. ± 6 in. at floor 97.
	10:28:22	First exterior sign of collapse (downward movement of building exterior). Tilting of the building section above the impact and fire area to due south as the structural collapse initiated. First exterior sign of downward movement of building at floor 98.
WTC 2	9:02:59	Exterior fireball from the east face of floor 82 and from the north face from floors 79 to 82. The deflagration prior to the fireballs may have caused a significant pressure pulse to act on floors above and below.
	9:21	Inward bowing of exterior wall columns on most of the east face from floors 78 to 83; maximum extent: 7 in. to 9 in. at floor 80.
	9:58:59	First exterior sign of collapse (downward movement of building exterior). The northeast corner tilted counterclockwise around the base of floor 82. Column buckling was then seen progressing across the north face and nearly simultaneously on the east face. Tilting of the building section above the impact and fire area to the east and south prior to significant downward movement of the upper building section. The tilt to the south did not increase any further as the upper building section began to fall, but the tilt to the east did increase until dust clouds obscured the view.

Within weeks of the destruction of the WTC, contractors of New York City had begun cutting up and removing the debris from the site. Members of the FEMA-sponsored and ASCE-led Building Performance Assessment Team, members of the Structural Engineers Association of New York, and Professor A. Astaneh-Asl of the University of California, Berkeley, CA, with support from the National Science Foundation, had begun work to identify and collect WTC structural steel from various recycling yards where the steel was taken during the clean-up effort. The Port Authority of New York and New Jersey (Port Authority) also collected structural steel elements for future exhibits and memorials.

Over a period of about 18 months, 236 pieces of steel were shipped to the NIST campus, starting about six months before NIST launched its Investigation. These samples ranged in size and complexity from a nearly complete three-column, three-floor perimeter assembly to bolts and small fragments. Figures 6–3 through 6–5 show some of the recovered steel pieces. Seven of the pieces were from WTC 5. The remaining 229 samples represented roughly 0.25 percent to 0.5 percent of the 200,000 tons of structural steel used in the construction of the two towers.

The collection at NIST included samples of all the steel strength levels specified for the construction of the towers. The locations of all structural steel pieces in WTC 1 and WTC 2 were uniquely identified by stampings (recessed letters and numbers) and/or painted stencils. NIST was successful in finding and deciphering these identification markings on many of the perimeter panel sections and core columns, in many cases using metallurgical characterization to complete missing identifiers. In all, 42 exterior panels were positively identified: 26 from WTC 1 and 16 from WTC 2. Twelve core columns were positively identified: eight from WTC 1 and four from WTC 2. Twenty-three pieces were identified as being parts of trusses, although it was not possible to identify their locations within the buildings.



Source: NIST.

Figure 6–3. Examples of a WTC 1 core column (left) and truss material (right).

Source: NIST.

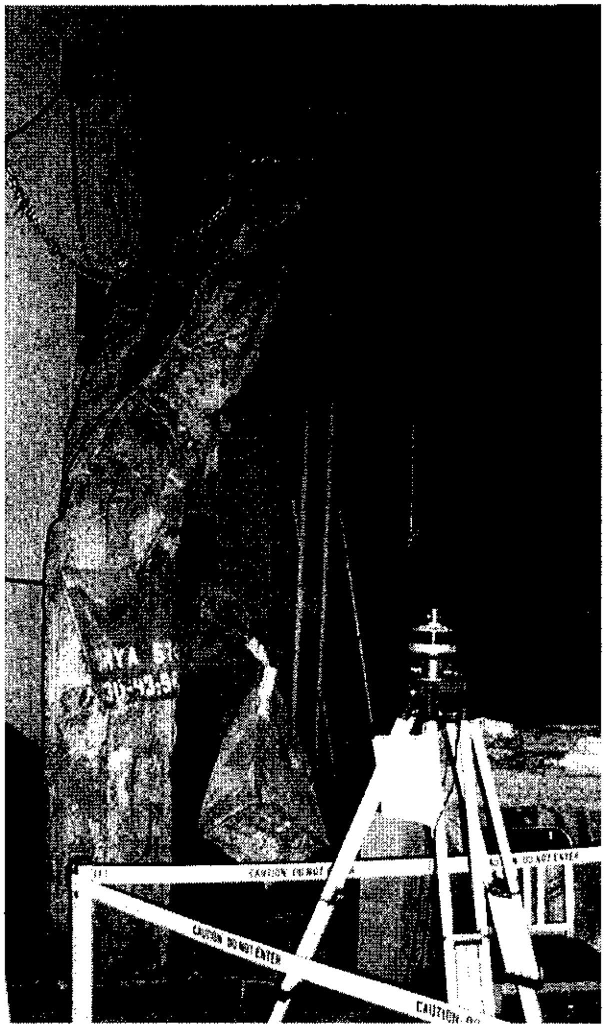
Figure 6–4. WTC 1 exterior panel hit by the fuselage of the aircraft.

Overlaying the locations of the specimens with photographs of the building exteriors following the aircraft impact (for perimeter columns and spandrels) and the extent-of-damage estimates (Section 6.8) (for core columns) enabled the identification of steel pieces near the impact zones. These included five specimens of exterior panels from WTC 1 and two specimens of core columns from each of the towers.

6.4.2 Mechanical and Physical Properties

NIST determined the properties of many of the recovered pieces for comparison with the original purchase requirements, comparison with the quality of steel from the WTC construction era, and input to the structural models used in the Investigation. Structural steel literature and producers' documents were used to establish a statistical basis for the variability expected in steel properties.

The properties of the steel samples tested were consistent with the specifications called for in the steel contracts. In particular, the yield strengths of all samples of the floor trusses were higher than called for in the original specifications. This was in part because the truss steels were supplied as a higher grade than specified. Overall, approximately 87 percent of all perimeter and core column steel tested exceeded the required minimum yield strengths specified in design documents. Test data for the remaining samples were below specifications, but were within the expected variability and did not affect the safety of the towers on September 11, 2001. Furthermore, lower strength values measured by NIST could be expected due to (a) differences in test procedures from those used in the qualifying mill tests and (b) the damaged state of the samples. The values of other steel properties were similar to typical construction steels of the WTC construction era. The limited tests on bolts indicated that their strengths were greater than the specified minimum, and they were stronger than contemporaneous literature would suggest as typical. The tested welds performed as expected.



Source: NIST.

Figure 6–5. WTC 1 exterior panel hit by the nose of the aircraft.

NIST measured the stress-strain behavior at room temperature (for modeling baseline performance), high temperature strength (for modeling structural response to fire), and at high strain rates (for modeling the aircraft impact). Based on data from published sources, NIST estimated the thermal properties of the steels (specific heat, thermal conductivity, and coefficient of thermal expansion) and creep behavior for use in the structural modeling of the towers' response to fire.

6.4.3 Damage Analysis

NIST performed extensive analyses of the recovered steel specimens to determine their damage characteristics, failure modes, and (for those near the fire zones) fire-related degradation. In some cases, assessment of enhanced photographic and video images of the towers enabled distinguishing between damage that occurred prior to the collapse and damage that occurred as a result of the collapse. Because the only visual evidence was from the outside of the buildings, this differentiation was only possible for the perimeter panel sections. The observations of fracture and failure behavior, confirmed by an Investigation contractor, were also used to guide the modeling of the towers' performance during impact and subsequent fires and to evaluate the model output.

For two of the five exterior panels from the impact zone of WTC 1, the general shape and appearance of the recovered pieces matched photographs taken just before the building collapse. Thus, NIST was able to attribute the observed damage to the aircraft impact. NIST also made determinations regarding the connections between structural steel elements:

- There was no evidence to indicate that the joining method, weld materials, or welding procedures were inadequate. Fractures of the columns in areas away from a welded joint were the result of stretching and thinning. Perimeter columns hit by the plane tended to fracture along heat-affected zones adjacent to welds.

- The failure mode of spandrel connections varied. At or above the impact zone, bolt hole tear-out was more common. Below the impact zone, it was more common for the spandrels to be ripped from the panels. There was no evidence that fire exposure changed these failure modes.

- The exterior column splices at the mechanical floors, which were welded in addition to being bolted, generally did not fail. The column splices at the other floors generally failed by bolt fracture.

- The perimeter truss connectors (or seats) below the impact zone in WTC 1 were predominantly bent down or torn off completely. Above the impact zone, the seats were as likely to be bent upward as downward. Core seats could not be categorized since their as-built locations could not be determined.

- Failure of core columns was a result of both splice connection failures and fracture of the columns themselves.

Examination of photographs showed that 16 of the exterior panels recovered from WTC 1 were exposed to fire prior to the building collapse. None of the nine recovered panels from within the fire floors of WTC 2 were directly exposed to fire. NIST used two methods to estimate the maximum temperatures that the steel members had reached:

- Observations of paint cracking due to thermal expansion. Of the more than 170 areas examined on 16 perimeter column panels, only three columns had evidence that the steel reached temperatures above 250 °C: east face, floor 98, inner web; east face, floor 92, inner web; and north face, floor 98, floor truss connector. Only two core column specimens had sufficient paint remaining to make such an analysis, and their temperatures did not reach 250 °C. NIST did not generalize these results, since the examined columns represented only 3 percent of the perimeter columns and 1 percent of the core columns from the fire floors.

- Observations of the microstructure of the steel. High temperature excursions, such as due to a fire, can alter the basic structure of the steel and its mechanical properties. Using metallographic analysis, NIST determined that there was no evidence that any of the samples had reached temperatures above 600 °C.

These results were for a very small fraction of the steel in the impact and fire zones. Nonetheless, these analyses indicated some zones within WTC 1 where the computer simulations should not, and did not, predict highly elevated steel temperatures.

6.5 INFORMATION GAINED FROM OTHER WTC FIRES

There had been numerous fires in the towers prior to September 11, 2001. From these, NIST learned what size fire WTC 1 and WTC 2 had withstood and how the tower occupants and the responders functioned in emergencies. While The Port Authority's records of prior fires were lost in the collapses, FDNY provided reports on 342 fires that had occurred between 1970 and 2001.

Most of these fires were small, and occupants extinguished many of them before FDNY arrival. Forty-seven of these fires activated one to three sprinklers and/or required a standpipe hose for suppression. Only two of the fires required the evacuation of hundreds of people. There were no injuries or loss of life in any of these fires, and the interruptions to operations within the towers were local.

A major fire occurred in WTC 1 on February 13, 1975, before the installation of the sprinkler system. A furniture fire started in an executive office in the north end of an 11th floor office suite in the southeast corner of the building. The fire spread south and west along corridors and entered a file room. The fire flashed over, broke seven windows, and spread to adjacent offices north and south. The air conditioning system turned on, pulling air into the return air ducts. Telephone cables in the vertical shafts were ignited, destroying the fire-retarded wood paneling on the closet doors. The fire emerged on the 12th and 13th floors, but there was little nearby that was combustible. The fire also extended vertically from the 9th to the 19th floors within the telephone closet. Eventually the fire was confined to 9,000 ft^2 of one floor, about one-fourth of the total floor area. The trusses and columns in this area had been sprayed with BLAZE-SHIELD D insulation to a specified ½ in. thickness. Four trusses were slightly distorted, but the structure was not threatened.

Only one major fire incident resulted in a whole-building evacuation. At 12:18 p.m. on February 26, 1993, terrorists exploded a bomb in the second basement underground parking garage in the WTC complex. The blast immediately killed six people and caused an estimated $300 million in damage. An intense fire followed and, although the flames were confined to the subterranean levels, the smoke spread into four of the seven buildings in the WTC complex. Most of the estimated 150,000 occupants evacuated the buildings, including approximately 40,000 from the affected towers. In all, 1,042 people were injured in the incident, including 15 who received blast-related injuries. The evacuation of the towers took over 4 hours. The incident response involved more than 700 firefighters (approximately 45 percent of FDNY's on-duty personnel at the time).

In addition, there was a fire on the 104th floor of WTC 1 on September 11, 2001, that apparently did not contribute to the eventual collapse, yet was quite severe. At 10:01 a.m., flames were first observed on the west face, and by 10:07 a.m., intense flames were emanating from several windows in the southern third of that face. The fire raged until the building collapsed at 10:28 a.m. Thus, the tower structure was able to withstand a sizable fire for about 20 min, presumably with the ceiling tile system heavily damaged and the truss system exposed to the flames. The 104th floor was well above the aircraft impact zone, so there should have been little damage to the sprayed fire-resistive material, which was the same (Table 5–3) as

on the floors where the fires led to the onset of the collapse. The photographic evidence showed no signs of column bowing or a floor collapse.

6.6 THE BUILDING STRUCTURAL MODELS

6.6.1 Computer Simulation Software

Structural modeling of each tower was required in order to:

- Establish the capability of the building, as designed, to support the gravity loads and to resist wind forces;
- Simulate the effects of the aircraft impacts; and
- Reconstruct the mechanics of the aircraft impact damage, fire-induced heating, and the progression of local failures that led to the building collapse.

The varied demands made different models necessary, and different software packages were used for each of these three functions. The reason for the choice in each case is presented in the next three sections of the report.

6.6.2 The Reference Models

Under contract to NIST, Leslie E. Robertson Associates (LERA) constructed a global reference model of each tower using the SAP2000, version 8, software. SAP2000 is a software package for performing finite element calculations for the analysis and design of building structures. These global, three-dimensional models encompassed the 110 stories above grade and the six subterranean levels. The models included primary structural components in the towers, resulting in tens of thousands of computational elements. The data for these elements came from the original structural drawing books for the towers. These had been updated through the completion of the buildings and also included most of the subsequent, significant alterations by both tenants and The Port Authority. LERA also developed reference models of a truss-framed floor, typical of those in the tenant spaces of the impact and fire regions of the buildings, and of a beam-framed floor, typical of the mechanical floors.

LERA's work was reviewed by independent experts in light of the firm's earlier involvement in the WTC design. It was that earlier work, in fact, that made LERA the only source that had the detailed knowledge of the design, construction, and intended behavior of the towers over their entire 38-year life span. The accuracy of the four models was checked in two ways:

- The two global models were checked by Skidmore, Owings & Merrill (SOM), also under contract to NIST, and by NIST staff. This entailed ensuring consistency of the models with the design documents, and testing the models, for example, to ensure that the response of the models to gravity and wind loads was as intended and that the calculated stresses and deformations under these loads were reasonable.
- The global model of WTC 1 was used to calculate the natural vibration periods of the tower. These values were then compared to measurements from the tower on eight dates of winds

ranging from 11.5 mph to 41 mph blowing from at least four different directions. As shown in Table 6–3, the N-S and E-W values agreed within 5 percent and the torsion values agreed within 6 percent, both within the combined uncertainty in the measurements and calculations.

- SOM and NIST staff also checked the two floor models for accuracy. These reviews involved comparison with simple hand calculations of estimated deflections and member stresses for a simply supported composite truss and beam under gravity loading. For the composite truss sections, the steel stress results were within 4 percent of those calculated by SAP2000 for the long-span truss and within 3 percent for the short-span truss. Deflections for the beams and trusses matched hand calculations to within 5 percent to 15 percent. These differences were within the combined uncertainty of the methods.

Table 6–3. Measured and calculated natural vibration periods (s) for WTC 1.

	Direction of Motion		
	N-S	E-W	Torsion
Average of Measured Data	11.4	10.6	4.9
Original Predicted Values	11.9	10.4	–
Reference Global Model Predictions	11.4	10.7	5.2

The few discrepancies between the developed models and the original design documents, as well as the areas identified by NIST and SOM as needing modification, were corrected by LERA and approved by NIST. The models then served as references for more detailed models for aircraft impact damage analysis and for thermal-structural response and collapse initiation analysis.

NIST also used these global reference models to establish the baseline performance of the towers under gravity and wind loads. The two key performance measures calculated were the demand-to-capacity ratio (DCR) and the drift.

- Demand is defined as the combined effects of the dead, live, and wind loads imposed on a structural component, e.g., a column. Capacity is the permissible strength for that component. Normal design aims at ensuring that DCR values for all components be 1.0 or lower. A value of DCR greater than 1.0 does not imply failure since designs inherently include a margin of safety.

- Drift is the extent of sway of the building under a lateral wind. Excessive deflection can cause cracking of partitions and cladding, and, in severe cases, building instability that could affect safety.

Using SAP2000, NIST found that, under original WTC design loads, a small fraction of the structural components had DCR values greater than 1.0. (Most DCR values of that small fraction were less than 1.4, with a few as high as 1.6.) For the perimeter columns, DCR values greater than 1.0 were mainly near the corners, on floors near the hat truss, and below the 9th floor. For the core columns, these members were on the 600 line between floors 80 and 106 and at core perimeter columns 901 and 908 for much of their height. (See Figure 1–5 for the column numbers.) One possible explanation to the cause of DCRs in excess of 1.0 may lie in the computer-based structural analysis and software techniques employed for this

baseline performance study in comparison with the relatively rudimentary computational tools used in the original design nearly 40 years ago.

As part of its wind analysis, NIST calculated the drift at the top of the towers to be about 5 ft in a nearly 100 mph wind—the wind load used in the original design. Common practice was, and is, to design for substantially smaller deflections; but drift was not, and still is not, a design factor prescribed in building codes.

The estimation of wind-induced loads on the towers emerged as a problem. Two sets of wind tunnel tests and analyses were conducted in 2002 by independent laboratories as part of insurance litigation unrelated to the NIST Investigation. The estimated loads differed by as much as 40 percent. NIST analysis found that the two studies used different approaches in their estimations. This difference highlighted limitations in the current state of practice in wind engineering for tall buildings and the need for standards in the field of wind tunnel testing and wind effects estimation.

6.6.3 Building Structural Models for Aircraft Impact Analysis

Ideally, the Investigation would have used the reference global models of the towers as the "targets" for the aircraft. However, this was not possible. The impact simulations required inclusion of both a far higher level of detail of the building components and also the highly nonlinear behavior of the tower and aircraft materials, and the larger model size could not be accommodated by the SAP2000 program. There were also physical phenomena for which algorithms were not available in this software. Another finite element package, LS-DYNA, satisfied these requirements and was used for the impact simulations.

Early in the effort, it became clear to both NIST and to ARA, Inc., the NIST contractor that performed the aircraft impact simulations, that the model had to "fit" on a state-of-the-art computer cluster and to run within weeks rather than months. To minimize the model size while keeping sufficient fidelity in the impact zone to capture the building deformations and damage distributions, various tower components were depicted with different meshes (different levels of refinement). For example, tower components in the path of the impact and debris field were represented with a fine mesh (higher resolution) to capture the local impact damage and failure, while components outside the impact zone were depicted more coarsely, simply to capture their structural stiffness and inertial properties. The model of WTC 1 included floors 92 through 100; the model of WTC 2 extended from floor 77 through floor 85. The combined tower and aircraft model of more than two million elements, at time steps of just under a microsecond, took approximately two weeks of computer time on a 12-noded computer cluster to capture the needed details of the fraction of a second it took for the aircraft and its fragments to come to rest inside the building.

The structural models, partially shown in Figures 6–6 through 6–9, included:

- Core columns and spliced column connections;
- Floor slabs and beams within the core;
- Exterior columns and spandrels, including the bolted connections between the exterior panels in the refined mesh areas; and
- Tenant space floors, composed of the combined floor slab, metal decking, and steel trusses.

They also included representations of the interior partitions and workstations. The live load mass was distributed between the partitions and cubicle workstations.

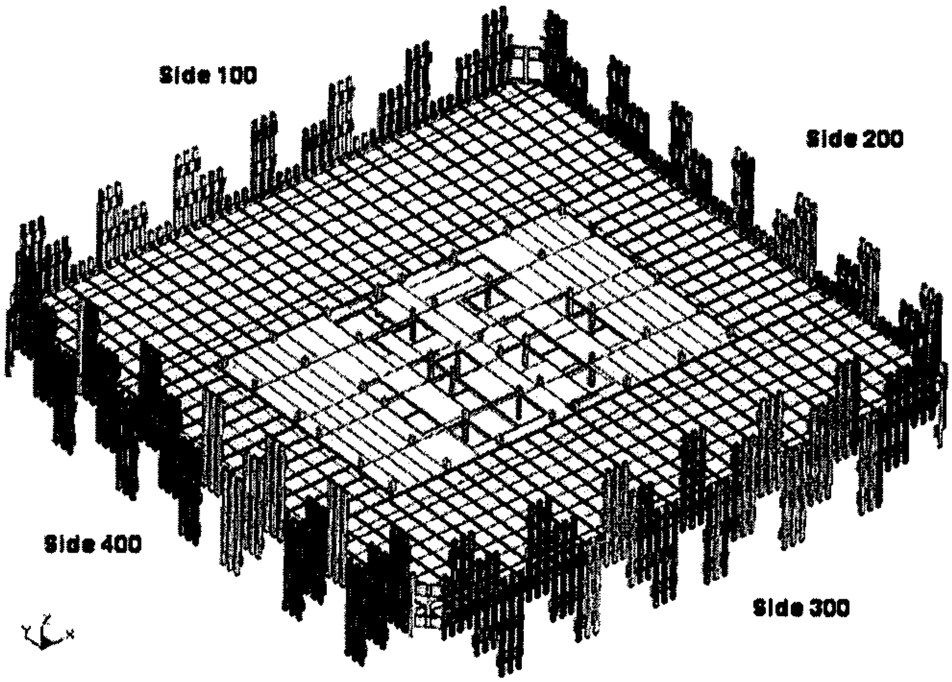


Figure 6–6. Structural model of the 96th floor of WTC 1.

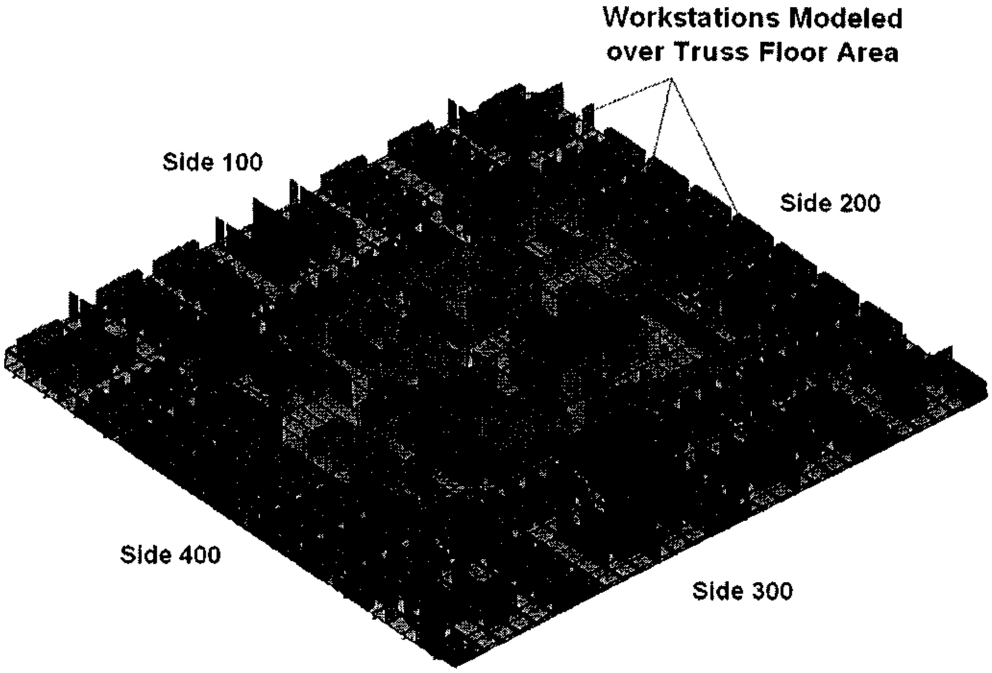


Figure 6–7. Model of the 96th floor of WTC 1, including interior contents and partitions.

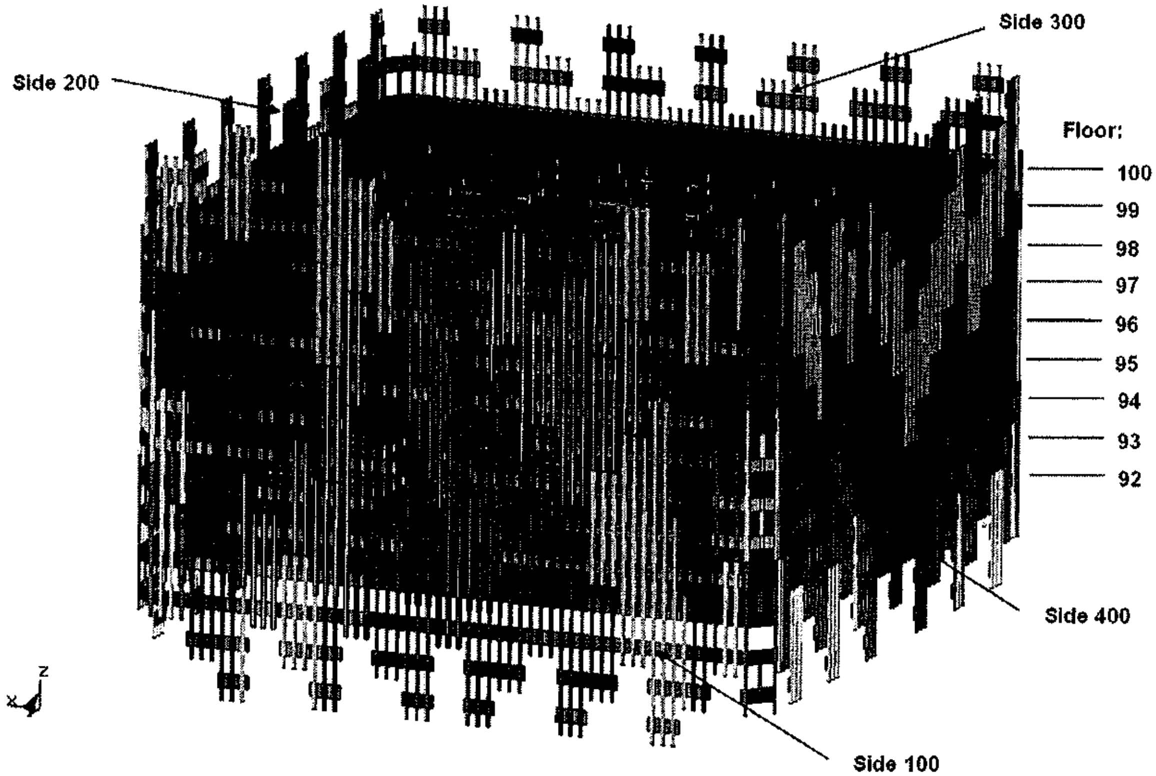


Figure 6–8. Multi-floor global model of WTC 1, viewed from the north.

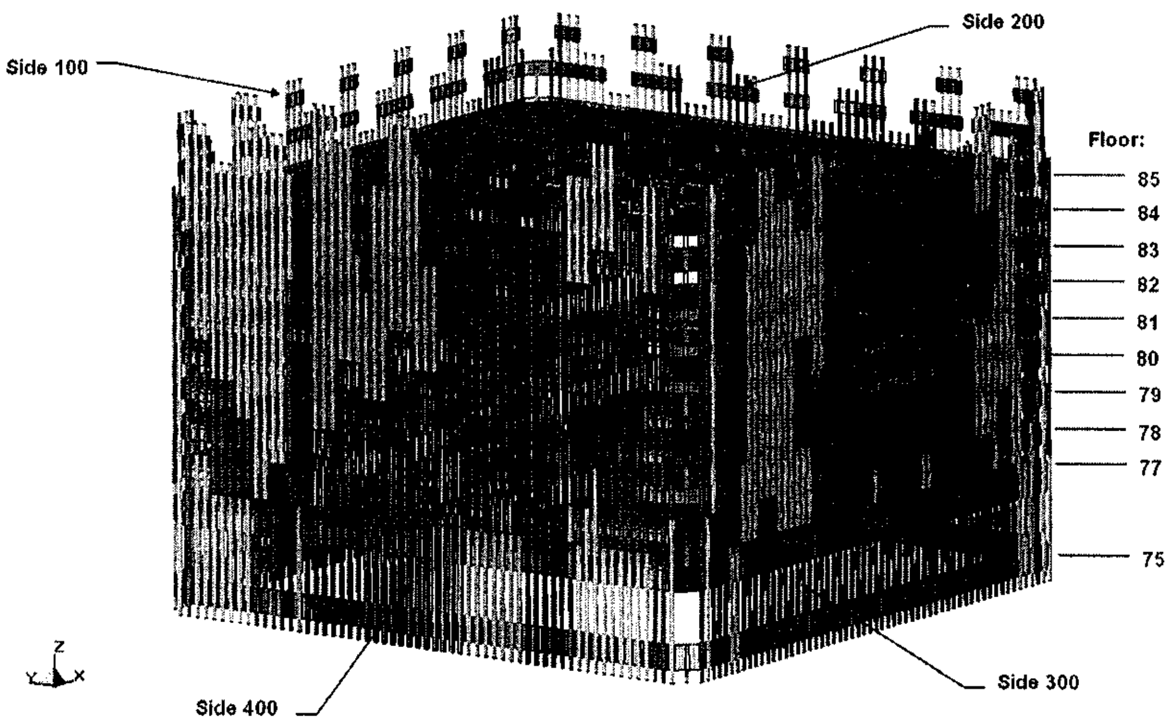


Figure 6–9. Multi-floor global model of WTC 2, viewed from the south.

Within these models, it was critical that the structural and furnishing materials behaved correctly when impacted by the aircraft or debris. For each grade of steel, the stress-strain behavior and the yield strength were represented using data from tests conducted at NIST. The weakening and failure of the concrete floor slabs were simulated using material models embedded in LS-DYNA. The primary influence of the nonstructural components on the impact behavior was their inertial contribution. Values for the resistance to rupture of gypsum panels and the fracture of the wood products in the workstations were obtained from published studies.

In order to complete the global models of the two towers, models of sections of the buildings were developed. As shown in Section 6.8.1, these submodels enabled efficient identification of the principal features of the interaction of the buildings with specific aircraft components.

6.6.4 Building Structural Models for Structural Response to Impact Damage and Fire and Collapse Initiation Analysis

The structural response and collapse analysis of the towers was conducted in three phases by NIST and Simpson Gumpertz & Heger, Inc. (SGH), under contract to NIST. The first phase included component and detailed subsystem models of the floor and exterior wall panels. The objectives of Phase 1 were to gain understanding into the response of the structure under stress and elevated temperatures, identify dominant modes of failure, and develop reductions in modeling complexity that could be applied in Phase 2. The second phase analyzed major subsystem models (the core framing, a single exterior wall, and full tenant floors) to provide insight into their behavior within the WTC global system. The third phase was the analysis of global models of WTC 1 and WTC 2 that took advantage of the knowledge gained from the more detailed and subsystem models. A separate global analysis of each tower helped determine the relative roles of impact damage and fires with respect to structural stability and sequential failures of components and subsystems and was used to determine the probable collapse initiation sequence.

Phase 1: Component and Detailed Subsystem Analyses

Floor Subsystem Analysis

The floors played an important role in the structural response of the WTC towers to the aircraft impact and ensuing fires. Prior to the development of a floor subsystem model, three component analyses were conducted, as follows:

- Truss seats. Figure 6–10 shows how an exterior seat connection was represented in the finite element structural model. The component analysis determined that failure could occur at the bolted connection between the bearing angle and the seat angle, and the truss could slip off the seat. Truss seat connection failure from vertical loads was found to be unlikely, since the needed increase in vertical load was unreasonable for temperatures near 600 °C to 700 °C.

- Knuckles. The "knuckle" was formed by the extension of the truss diagonals into the concrete slab and provided for composite action of the steel truss and concrete slab. A model was developed to predict the knuckle performance when the truss and concrete slab acted compositely.

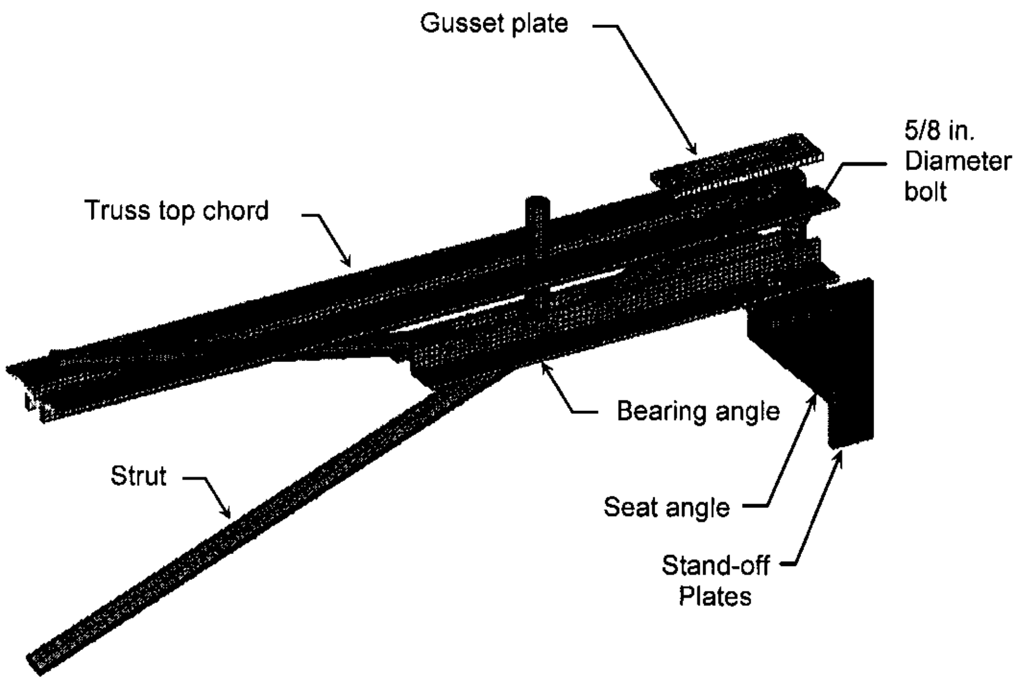


Figure 6–10. Finite element model of an exterior truss seat.

- Single composite truss and concrete slab section. A floor section was modeled to investigate failure modes and sequences of failures under combined gravity and thermal loads. The floor section was heated to 700 °C (with a linear thermal gradient through the slab thickness from 700 °C to 300 °C at the top surface of the slab) over a period of 30 min. Initially the thermal expansion of the floor pushed the columns outward, but with increased temperatures, the floor sagged and the columns were pulled inward. Knuckle failure was found to occur mainly at the ends of the trusses and had little effect on the deflection of the floor system. Figure 6–11 shows that the diagonals at the core (right) end of the truss buckled and caused an increase in the floor system deflection, ultimately reaching approximately 42 in. Two possible failure modes were identified for the floor-truss section: sagging of the floor and loss of truss seat support.

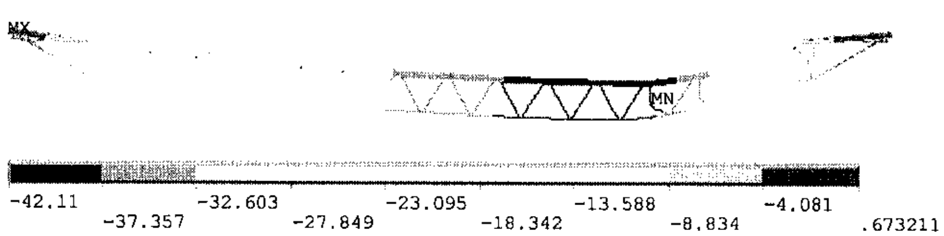


Figure 6–11. Vertical displacement at 700 °C.

A finite element model of the full 96th floor of WTC 1 was translated from the SAP2000 reference models into ANSYS 8.1 for detailed structural evaluation (Figure 6–12)[14]. The two models generated comparable predictions of the behavior under dead or gravity loads.

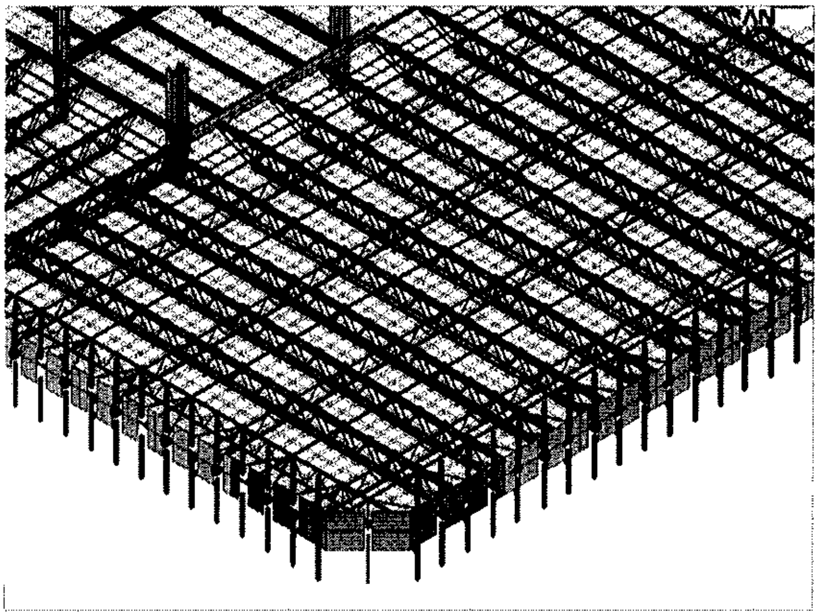


Figure 6–12. ANSYS model of 96th floor of WTC 1.

The model was used to evaluate structural response under dead and live loads and elevated temperatures, identify failure modes and associated temperatures and times to failure, and identify reductions in modeling complexity for global models and analyses. The structural response included thermal expansion of steel and concrete members, temperature-dependent properties of steel and concrete that affected material stiffness and strength, and bowing or buckling of structural members. The deformation and failure modes identified were floor sagging between truss supports, floor sagging resulting from failure of a seat at either end of the truss, and failure of the floor subsystem truss supports.

Exterior Wall Subsystem

The exterior walls played an important role in each tower's reaction to the aircraft impact and the ensuing fires. Photographic and video evidence showed inward bowing of large sections of the exterior walls of both towers just prior to the time of collapse.

A finite element model of a wall section was developed in ANSYS for evaluation of structural response under dead and live loads and elevated structural temperatures, determination of loads that would have caused buckling, and identification of reductions of modeling complexity for global models and analyses. The modeled unit consisted of seven full column/spandrel panels (described in Section 1.2.2) and portions of four other panels. The model was validated against the reference model developed by LERA (Section 6.6.2) by comparing the stiffness for a variety of loading conditions.

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[14] ANSYS allowed including the temperature-varying properties of the structural materials, a necessary feature not available in SAP 2000.

The model was subjected to several gravity loads and heating conditions, several combinations of disconnected floors, and pull-in from sagging floors until the point of instability. In one case, the simulation assumed three disconnected floors, and the top of the wall subsystem was subjected to "push-down" analysis, i.e., an increasing force to provide a measure of remaining capacity in the wall section.

The model captured possible failure modes due large lateral deformations, column buckling from loss of support at floor truss seats and diagonal straps, failure of column splice bolts, and failure of spandrel splice bolts or tearing of spandrel or splice plates at bolt holes. The model also showed:

- Large deformations and buckling of the spandrels could be expected at high temperatures, but they did not significantly affect the stability of the exterior columns and generally did not need to be precisely modeled in the tower models.
- Partial separations of the spandrel splices could be expected at elevated temperatures, but they also did not significantly affect the stability of the exterior columns.
- Exterior column splices could be expected to fail at elevated temperatures and needed to be accurately modeled.
- Plastic buckling of columns, with an ensuing rapid reduction of load, was to be expected at extremely high loads and at low temperatures.
- The sagging of trusses resulted in approximately 14 kip of inward pull per truss seat on the attached perimeter column.

Phase 2: Major Subsystem Analyses

Building on these results, ANSYS models were constructed of each of the three major structural subsystems (core framing, a single exterior wall, and full composite floors) for each of the towers. The models were subjected to the impact damage and elevated temperatures from the fire dynamics and thermal analyses to be described later in this chapter.

Core Framing

The two tower models included the core columns, the floor beams, and the concrete slabs from the impact and fire zones to the highest floor below the hat truss structure: from the 89th floor to the 106th floor for WTC 1 and from the 73rd floor to the 106th floor for WTC 2. Within these floors, aircraft-damaged structural components were removed. Below the lowest floors, springs were used to represent the stiffness of the columns. In the models, the properties of the steel varied with temperature, as described in Section 5.5.2. This allowed for realistic structural changes to occur, such as thermal expansion, buckling, and creep.

The forces applied to the models included gravity loads applied at each floor, post-impact column forces applied at the top of the model at the 106th floor, and temperature histories applied at 10 min intervals with linear ramping between time intervals.

Under these conditions, the investigators first determined the stability of the core under impact conditions and then its response under thermal loads:

- In WTC 1, the core was stable under Case A (base case) impact damage, but the model could not reach a stable solution under Case B (more severe) impact damage.
- The WTC 1 core became unstable under Case A impact damage and Case B thermal loads as it leaned to the northwest (due to insulation dislodged from the northwest corner column); the core model was restrained in horizontal directions at floors above the impact zone half way through the thermal loads.
- The WTC 2 core was stabilized for Case C (base case) by providing horizontal restraint at all floors representing the restraint provided by the perimeter wall to resist leaning to the southeast. A converged, stable solution was not found for Case D (more severe) impact damage.
- The WTC 2 stabilized core model for Case C impact damage was subjected to Case D thermal loads.

Following each simulation, a pushdown analysis was performed to determine the core's reserve capacity. The analysis results showed that:

- The WTC 1 isolated core structure was most weakened from thermal effects at the center of the south side of the core. (Smaller displacements occurred in the global model due to the constraints of the hat truss and floors.)
- The WTC 2 isolated core was most weakened from thermal effects at the southeast corner and along the east side of the core. (Larger displacements occurred in the global model as the isolated core model had lateral restraints imposed that were somewhat stiffer than in the global model.)

Composite Floor

The composite floor model was used to determine the response of a full floor to Case A and B thermal loads for WTC 1 floors and Case C and D thermal loads for WTC 2 floors. It included:

- A reduced complexity truss model, validated against the single truss model results.
- Primary and bridging trusses, deck support angles, spandrels, core floor beams, and a concrete floor slab.
- Fire-generated local temperature histories applied at 10 min intervals with linear ramping between time intervals.
- Temperature-dependent concrete and steel properties, except for creep behavior.